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Simulations of 4D edge transport and dynamics using the TEMPEST gyrokinetic code*

T.D. Rognlien, B.I. Cohen, R.H. Cohen, W.M. Nevins,
M.R. Dorr, J.A.F. Hittinger, G.D. Kerbel M.V. Umansky,
A. Xiong, and X.Q. Xu

Lawrence Livermore National Laboratory

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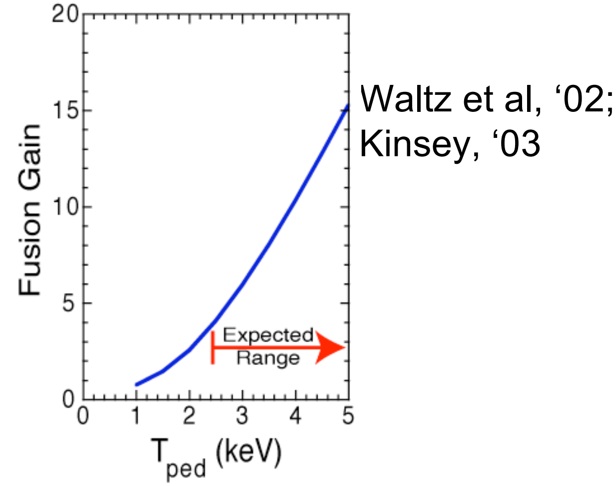
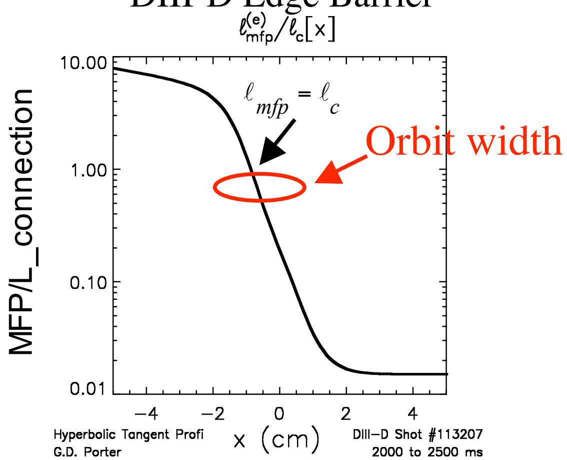
Goal is development of efficient continuum edge gyrokinetic (GK) code, i.e., evolve f(x,v) on 5D mesh

Motivation:

- **Kinetic code needed for fusion plasmas**
  - finite ion drift-orbit width $\Delta_\perp$
  - collis. || mean free path ~ connec. length
  - ITER pedestal deeply in kinetic regime; divertor strongly collisional
- **Gyrokinetic(2v), because still $\omega << \omega_c$**
  - but GK extensions required because
    - $\Delta_\perp \sim L_p$
    - $e\phi/T_e \sim 1$
    - see H.Qin Contrib. Plasma Phys., '06
- **Utilize reservoir of advanced skills by partnering with mathematical and comp. science community**





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A few definitions and a timeline (approx.) will help in orientation:

Edge Simulation Laboratory (ESL)

TEMPEST: a 4D (2r,2v) → 5D (3r,2v) continuum gyrokinetic edge code

Prototype codes: e.g., 3D (1r,2v) eikonal continuum gyrokinetic code

TBD-name: a next-generation (4D) 5D continuum gyrokinetic edge code

LLNL internal funds

Direct DOE funds -
National collaboration

2004 2005 2006 2007 2008 2009 …

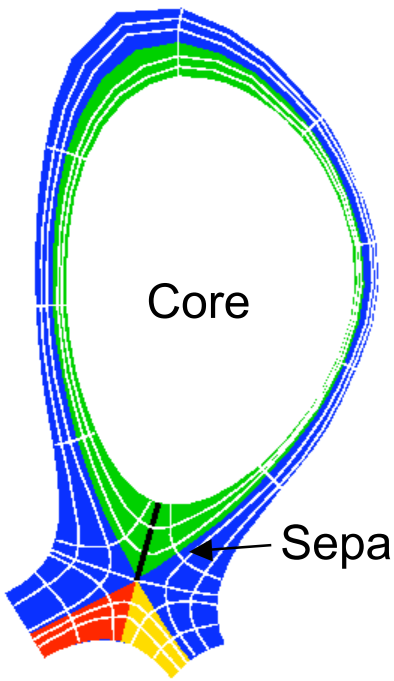
Calendar Year →

Why consider continuum?
Because features are attractive for difficult edge issues

- **Avoid discrete-particle noise that is a concern for edge because**
  - Inapplicability of δf (can have large fluctuations; *a priori* unknown background f; growing weights for long-time)
  - Still need accuracy in regions and times with small fluctuations
  - Large density variation across region
- **Nonlinear gyrokinetic PIC collisions can be expensive in the strongly collisional, short mean-free-path limit**
- **Advanced fluid numerical techniques available for continuum**
  - High-order discretizations
  - Adaptive Mesh Refinement in v and x -- high res. only where needed
  - Implicit time-stepping techniques
- **Successful core continuum GK codes (GS2, GYRO, GENE)**
- **Allows comparison with developing PIC codes**

Gyrokinetic equation has been implemented in the continuum TEMPEST for the edge

$$
\begin{aligned}
\frac{\partial F_\alpha}{\partial t} &+ \bar{\mathbf{v}}_{\mathrm{d}} \cdot \nabla_\perp F_\alpha + (\bar{v}_{\|\alpha} + v_{Banos}) \nabla_\| \partial F_\alpha \\
&+ \left[q \frac{\partial \langle \Phi_0 \rangle}{\partial t} + \bar{\mu} \frac{\partial B}{\partial t} - \frac{qB}{B^*} \bar{v}_\| \nabla_\| \langle \delta\phi \rangle - q \mathbf{v}_{\mathrm{d}}^0 \cdot \bar{\nabla} \langle \delta\phi \rangle \right] \frac{\partial F_\alpha}{\partial E_0} \\
&= C(F_\alpha, F_\alpha),
\end{aligned}
$$



- **GK F-equation discretized with high order (4th); Fokker-Planck collisions**
- **Full-f and δf options available**
- **Circular & divertor geom.; 2D equilibrium potential**
- **Runnable as**
  - 4-D for transport with F($\Psi,\theta,\varepsilon,\mu$), or
  - 5-D for turbulence with F($\Psi,\theta,\phi,\varepsilon,\mu$) - beginning
- **Extensions planned:**
  - sources/sinks
  - model transport coefficients for initial anomalous transp.
  - generalized GK equations (see Qin)
  - optional fluid equations in same framework
  - *field-aligned coordinates for evolving B

We have implemented and are using a gyrokinetic Poisson field solver

$$\left(\sum_\alpha \frac{\rho_\alpha^2}{2\lambda_{D\alpha}^2}\right)\nabla_\perp^2\Phi + \left(\sum_\alpha \frac{\rho_\alpha^2}{2\lambda_{D\alpha}^2}\nabla_\perp \ln N_\alpha\right)\cdot\nabla_\perp\Phi + \nabla^2\Phi$$

$$= -4\pi e\left(\sum_\alpha Z_\alpha N_\alpha - n_e\right) - \sum_\alpha \frac{\rho_\alpha^2}{2\lambda_{D\alpha}^2}\frac{1}{N_\alpha Z_\alpha e}\nabla_\perp^2 p_{\perp\alpha}$$

Electron model presently Boltzmann ($\theta \rightarrow$ poloidal):

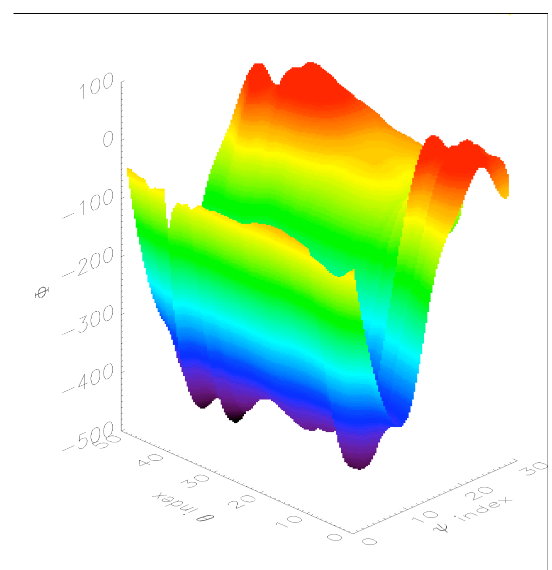
$$\boxed{n_e(\theta,t) = A \exp(e\phi/T_e) \,/\, \langle \exp(e\phi/T_e)\rangle_\theta}$$

1) $A = \langle n_i(\theta,t=0)\rangle$; preserves initial n_e perturb.

2) $A = \langle n_i(\theta,t)\rangle$; gives $\langle n_e\rangle_\theta = \langle n_i\rangle_\theta$ at all times

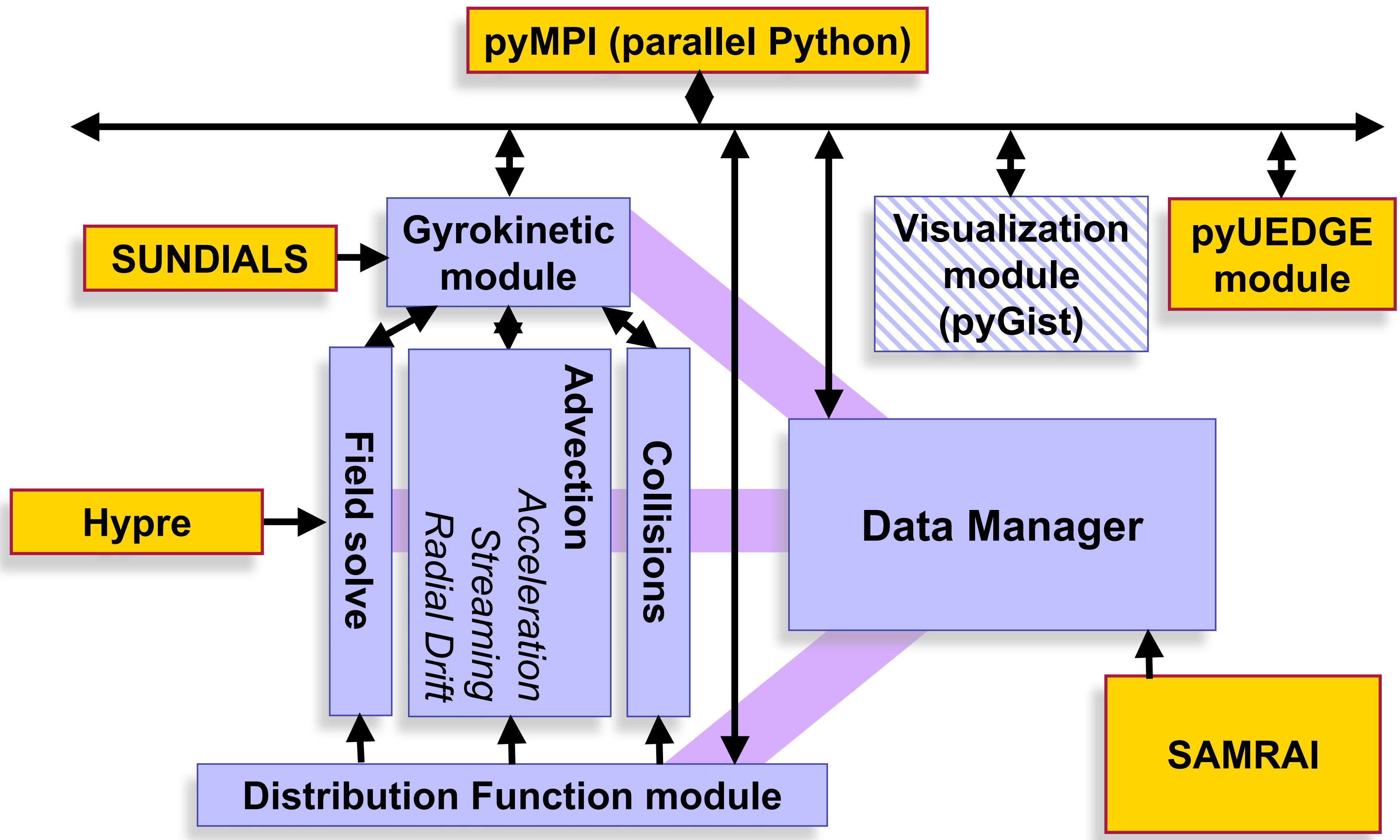
3) $A = \langle \overline{n_i}(t)\rangle$; giving ambipolar plate loss

- **Use *Hypre* library of parallel linear algebra solvers (GMRES now) and preconditioners (Gauss-Seidel now)**



Electromagnetic prototyping begins in 2007

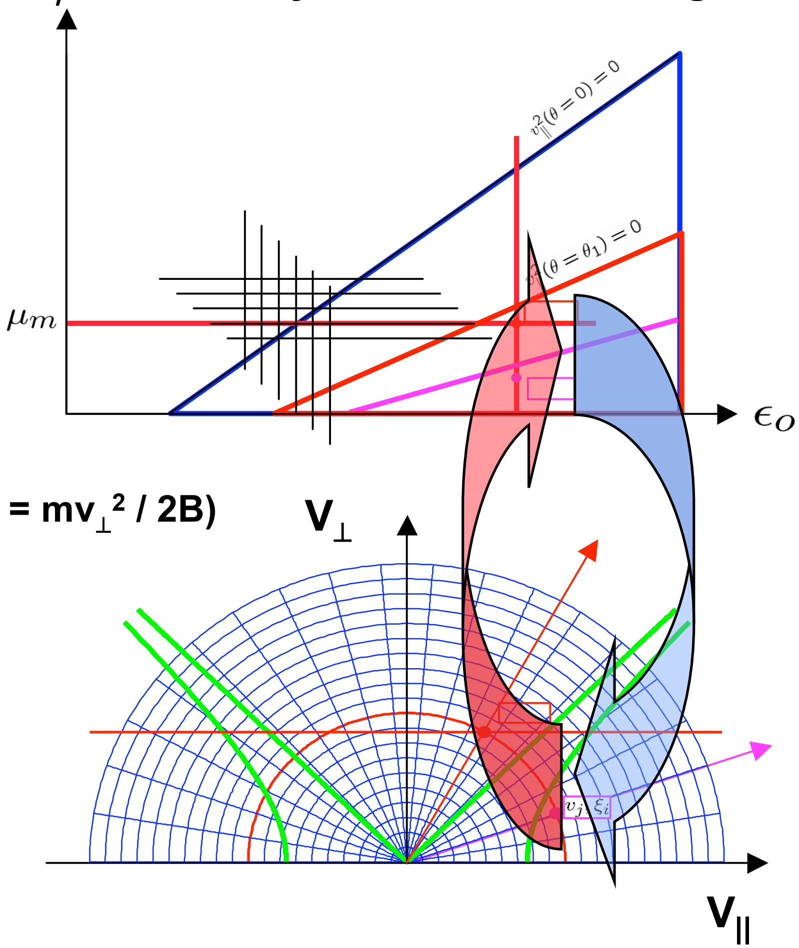
We have developed the code in a modern framework using advanced solvers; added physics “born parallel”



We have identified and implemented particle conservation as key for collisions and Poisson solutions

Collisions and f-moments have been updated to conservative finite-volume form

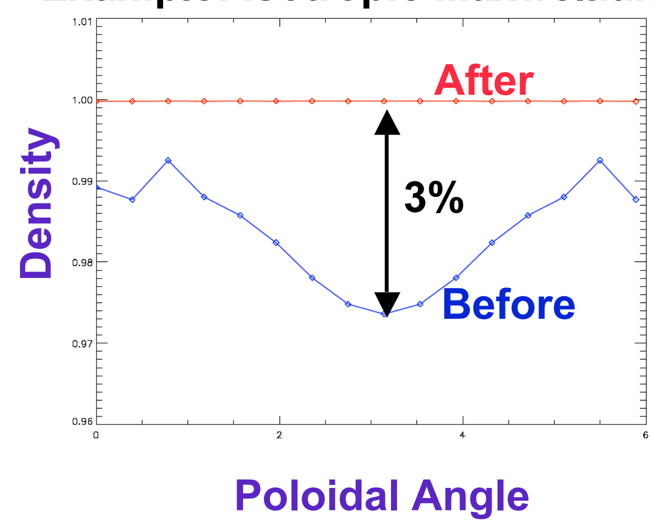
f mapped between (E,μ) and (μ,$v_{||}$); accurately resolve cell-averaged f



(μ = m$v_\perp^2$ / 2B)

Improvement in density moment with fully-conservative technique - needed for Poisson solves

Example: isotropic Maxwellian



We have verified different aspects of the 3D & 4D TEMPEST on known physics problems

Key physics aspects have been tested

1. **Collisional scattering into velocity-space loss cones**
   - magnetically trapped ions scattering into loss-cones near magnetic separatrix
   - electrons are potentially confined by divertor/wall sheath potentials - non-Maxwellian, high-energy tails can develop

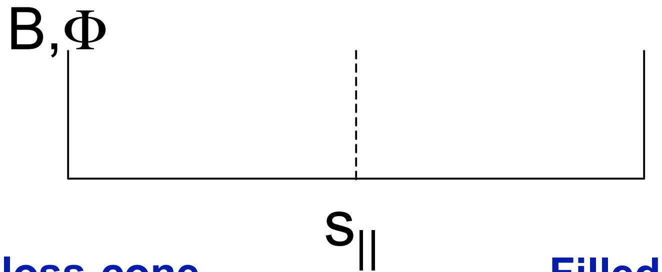
2. **Neoclassical flow for core ions**
   - high temperature and low turbulence for H-mode can result in neoclassical ion transport being important

3. **Electrostatic field generation and geodesic acoustic mode damping**
   - shear-flow and zonal flows can strongly affect turbulence suppression

Test 1: TEMPEST recovers theoretical v-space transport for combined B-, Φ-well using modest mesh resolution

(E,μ) mesh = (50,40)

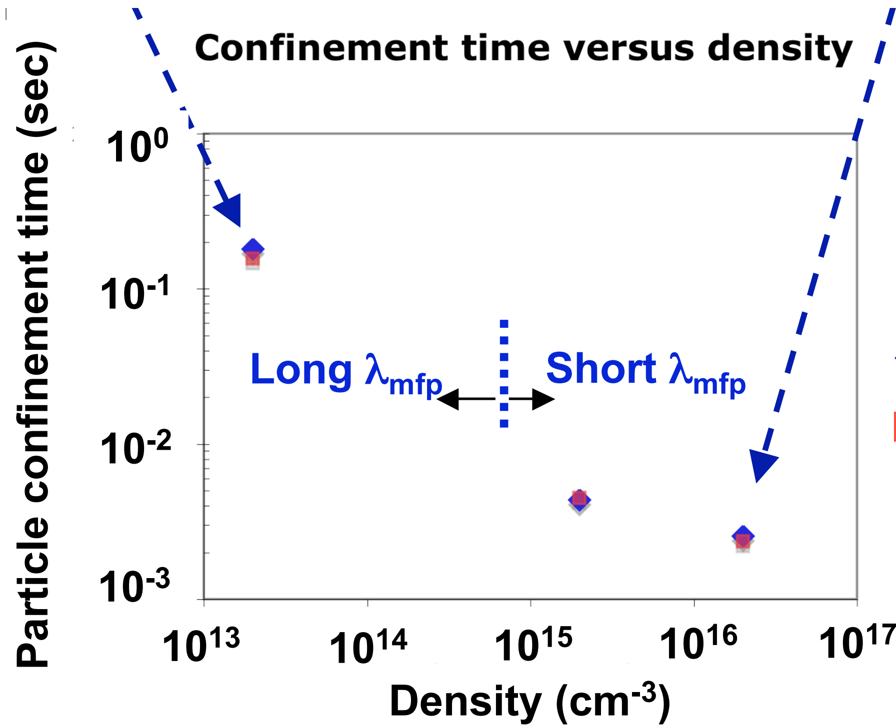
$R_m = 2$; $e\phi/T_e = 2$



(finite-difference FP version results here)

Empty loss-cone (Pastukhov); $\sim\tau_p$

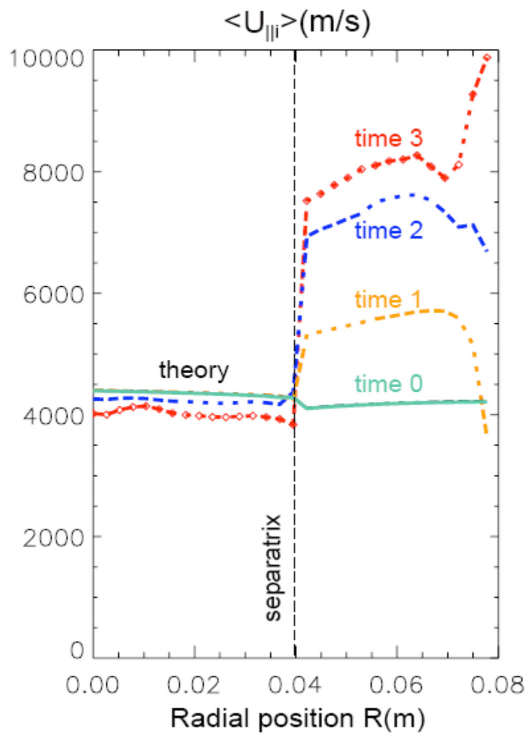
Filled loss-cone (collisional); $\sim\tau_c$



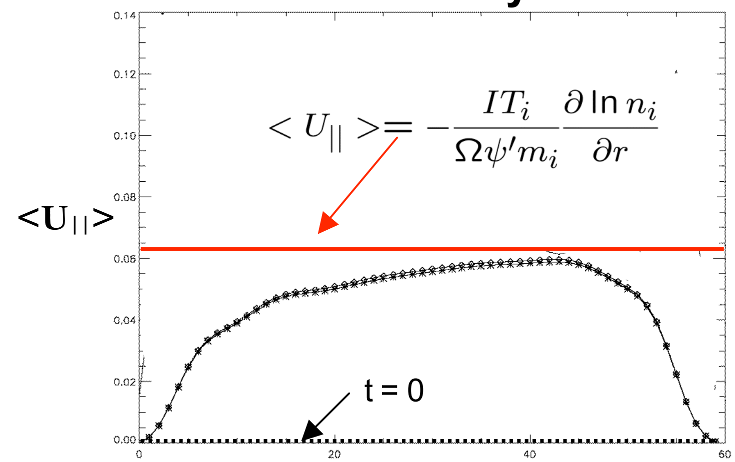
♦ Theory $\boxed{\tau = \tau_p + \tau_c}$

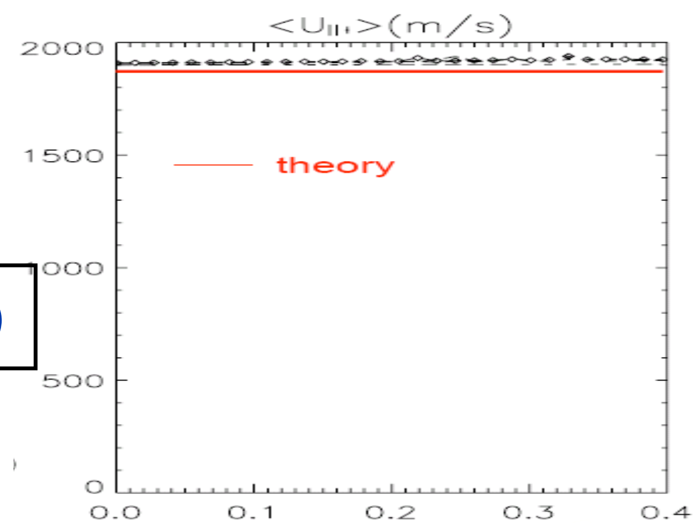
■ Simulation

Test 2: TEMPEST 4D simulation results agree with neoclassical theory in low collisionality regime



Core only





Radial Position R (m)

$$\boxed{\langle U_{i||}\rangle = -E_r/B_p - (T_i / eB_p)(\partial/\partial r)(\ln P_i - k \ln T_i)}$$

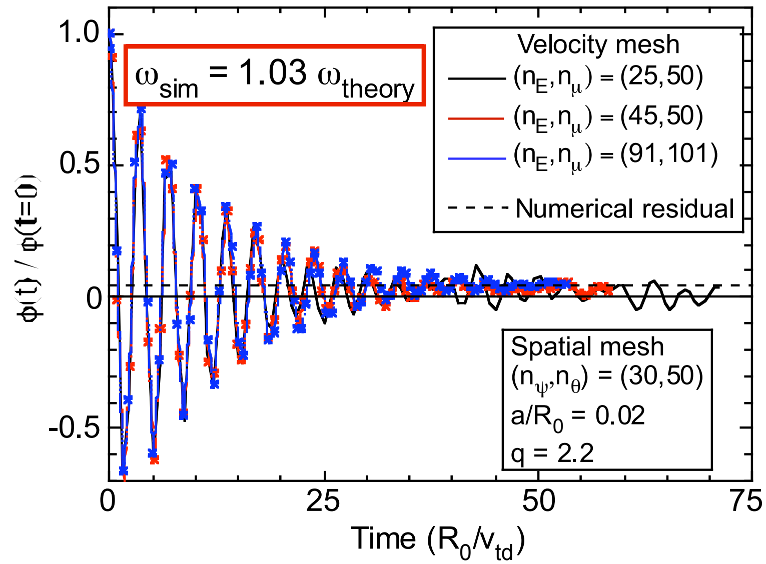
and k depends on collisionality regime

Simplest test for
$E_r = 0$ and $\partial T_i/\partial r = 0$

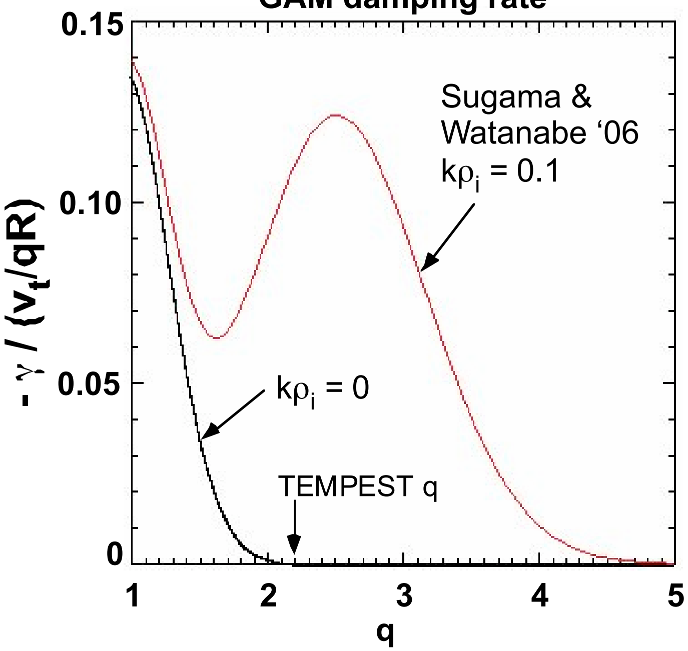
Test 3: Solution of electrostatic potential; damping of geodesic acoustic modes (GAM) follows theory

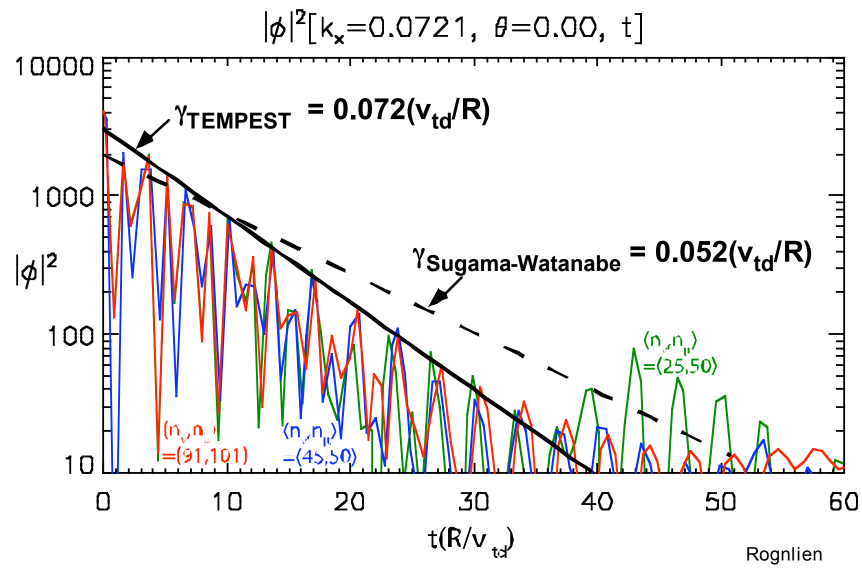
- **Initial 2D fixed n_e pertubation cause ions/poten. to relax as GAM**
- **Sugama, Watanabe show damping sensitive to $k\rho_i$ at large q (bananas)**
- **TEMPEST example follows the larger damping from finite $k\rho_i$ and q**

TEMPEST results



GAM damping rate





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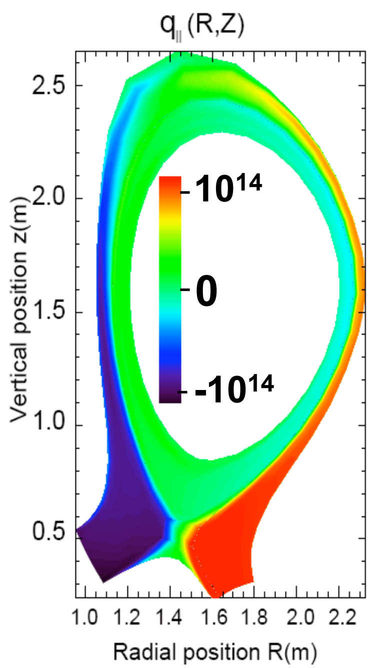
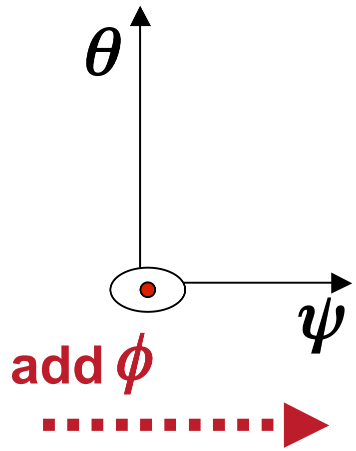
5D algorithms have now been coded in TEMPEST

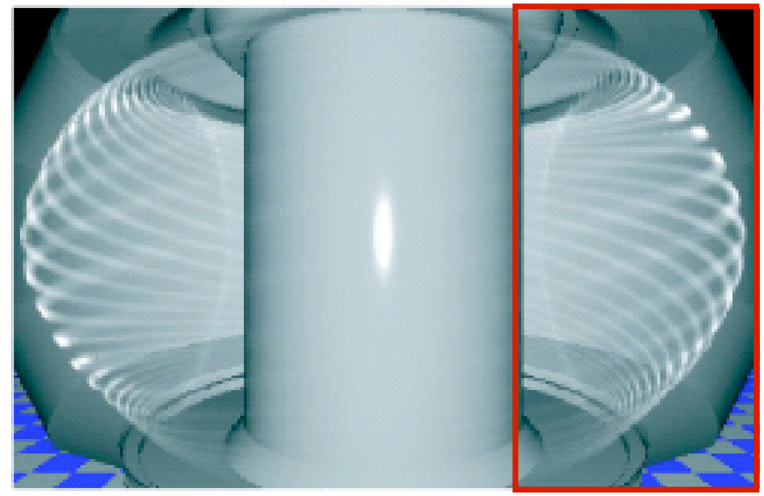
4D neoclassical transport



(ψ,θ,E_0,μ)



Full turbulence requires 5D torodial physics



$(\psi,\theta,\phi,E_0,\mu)$

e.g., modes from ELITE (PoP, 2005)

- **TEMPEST has been generalized to**
  - 3D spatial differencing competed for GK and Poisson Eqns.
  - Field-aligned coordinates with interpolation & index shifting for shear
  - Full 5D testing has begun targeting linear mode growth initially

Summary

- Recently developed continuum TEMPEST (LLNL) has demonstrated expected physics in 3D and 4D verification tests
- TEMPEST algorithms, including the GK Poisson equation, have by generalized to 5D and testing has begun
- U.S. continuum code work has now been expanded to multiple institutions through the recently initiated ESL project to develop the next generation code